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Energy Flowchart Scenarios of Future U.S. Energy Use Incorporating Hydrogen Fueled Vehicles

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Lawrence Livermore National Laboratory

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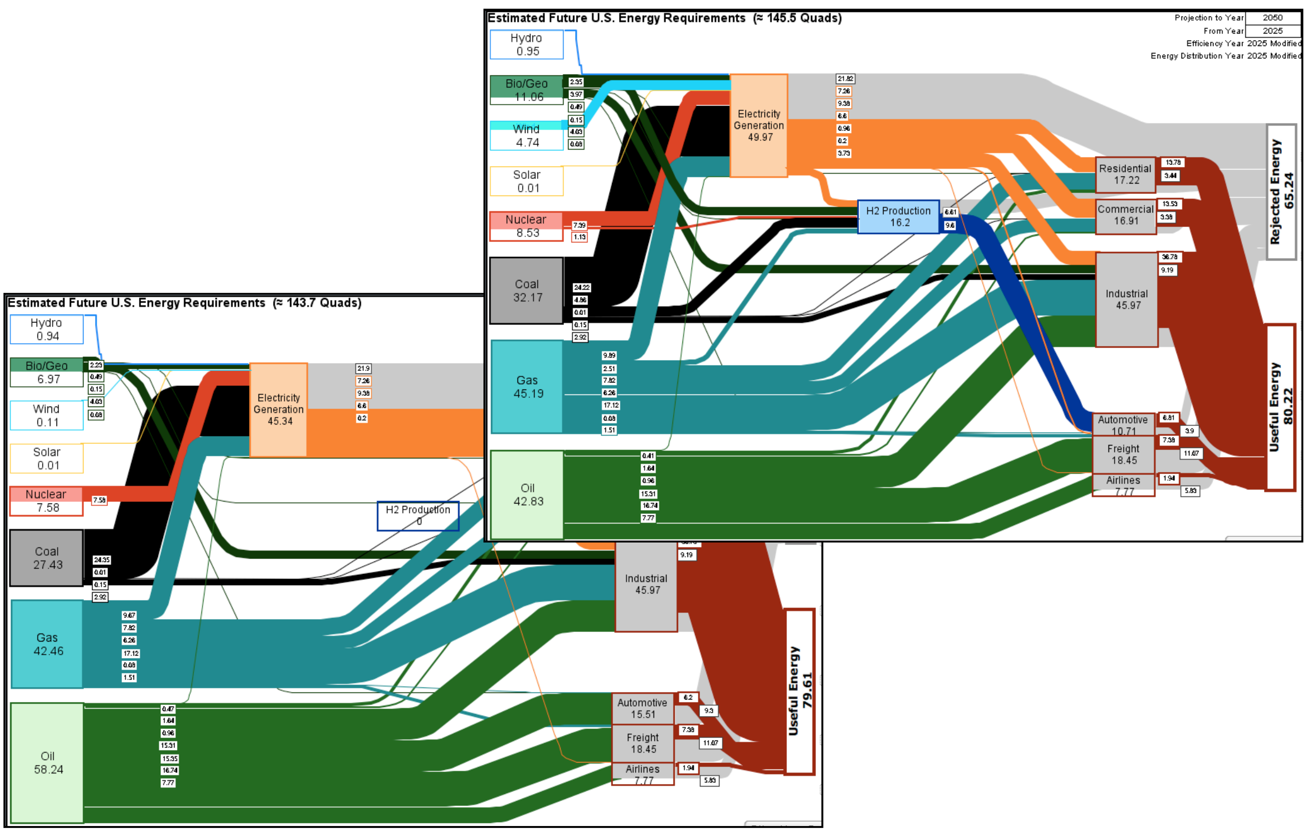

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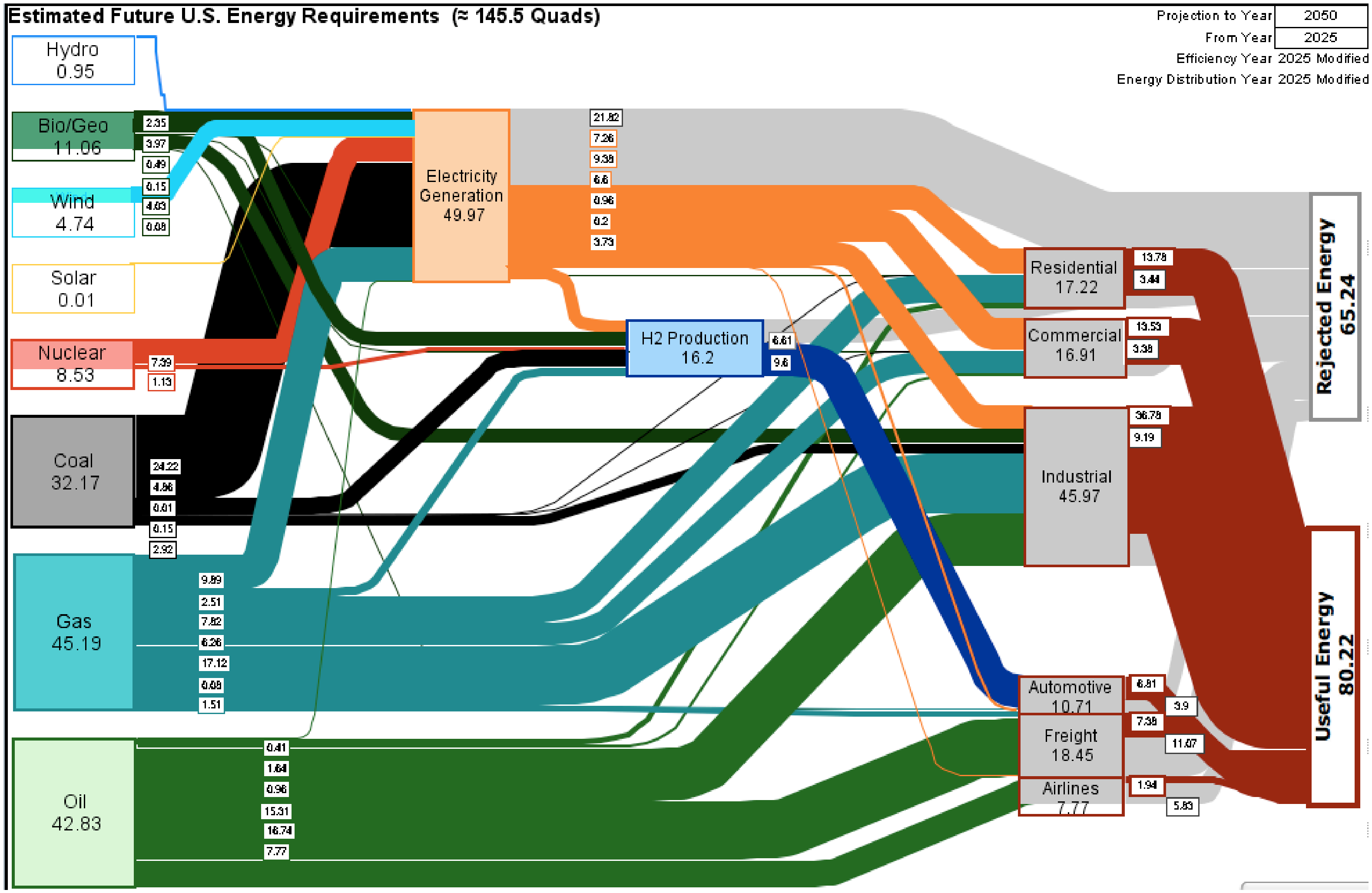
Executive Summary

This project has adapted LLNL energy flowcharts of historical U.S. energy use drawn from the DOE Energy Information Administration (EIA) data to include scenarios involving hydrogen use. A flexible automated process for preparing and drawing these flowcharts has also been developed. These charts show the flows of energy between primary sectors of the economy so that a user can quickly understand the major implications of a proposed scenario. The software can rapidly generate a spectrum of U.S. energy use scenarios in the 2005-2050 timeframe, both with and without a transition to hydrogen-fueled transportation. These scenarios indicate that fueling 100% of the light duty fleet in 2050 (318 million 80 mpg-equivalent compressed hydrogen fuel cell vehicles) will require approximately 100 million tonnes (10.7 quads) of H_2/year, reducing petroleum use by at least 7.3 million barrels of oil/day (15.5 quads/yr).

Linear extrapolation of EIA's 2025 reference projection to 2050 indicates approximate U.S. primary energy use of 180 quads/yr (in 2050) relative to current use of 97 quads/yr (comprising 39 quads/yr of petroleum). Full deployment of 50% efficient electricity generation technologies for coal and nuclear power and improvements in gasoline light-duty vehicle fleet fuel economy to 50 mpg would reduce projected U.S. primary energy consumption to 143 quads/yr in 2050, comprising 58 quads/yr (27 million bbl/day) of petroleum. Full deployment of H_2 automobiles by 2050 could further reduce U.S. petroleum dependence to 43 quads/yr. These projections indicate that substantial steps beyond a transition to H_2 light-duty vehicles will be necessary to reduce future U.S. petroleum dependence (and related greenhouse gases) below *present* levels.

A flowchart projecting future U.S. energy flows depicting a complete transition by 2050 to compressed hydrogen light-duty vehicles is attached on the following page (corresponding to scenario 7 in the Appendix). It indicates that producing 100 billion kilograms of hydrogen fuel annually (10.7 quads/yr) from a balanced blend of primary energy sources will likely require 16.2 quads of primary energy input, with an additional 0.96 Quads of electricity for hydrogen storage. These energy flows are comparable to or smaller than projected growth in individual primary energy sources over the 2005-2050 timeframe except perhaps the case of windpower.



U.S. Energy flow scenario for the year 2050, based on linear extrapolation of EIA 2025 reference projection modified to include a) 50% efficient electricity generation, and b) 318 million "80 mpg" H_2 fuel cell vehicles

LLNL Energy Flowchart Methodology

Since the mid-1970's Lawrence Livermore National Laboratory (LLNL) has published energy flowcharts or "spaghetti" diagrams for *comprehensive* visualization of annual U.S. energy use patterns. The flowcharts are based on historical data published by the Energy Information Administration (EIA) in its Annual Energy Review. The most recent flowchart showing United States energy flows for 2001 is shown in figure 1.

The flowchart can be read left to right beginning with boxes representing *primary* energy resources (coal, oil, gas, nuclear, hydropower, and other renewables) on the left. Lines flow from these resources to boxes on the right representing electricity generation or end-uses (residential/commercial, industrial, non-fuel, and transportation). The line *widths* correspond quantitatively to the amount of energy delivered to each use from each source. Electricity generation and end-uses are less than 100% efficient. The amount(s) of useful energy (work) and rejected energy (heat) from each process and end-use are also estimated quantitatively with additional lines aggregated both graphically and numerically on the right to give the overall amounts of useful and rejected energy consumed each year in the United States.

Figure 1 permits several important overall observations about current U.S. energy use. First, the majority of primary energy (~70%) is consumed in 2 processes: electricity generation and transportation. Second, these sectors account for an even larger fraction (~85%) of the rejected energy throughout the United States. Third, these sectors are vertically integrated. Coal is essentially used only in electric generation (which it dominates), and petroleum is used essentially for transportation (for which it supplies more than 95% of the primary energy).

Adaptation of Energy Flowcharts to Scenarios of Hydrogen Fuel Use

Hydrogen fuel has the potential to dramatically change this picture over the next 50 years. Like electricity, hydrogen is an energy carrier that can be made from any energy source. Unlike electricity, hydrogen can be universal, serving all transportation modes. And unlike other fuels, hydrogen use evolves no tail-pipe air pollution or carbon dioxide (CO_2) emissions *at the point of use*. With the advent of the Freedom Car and Freedom Fuel initiatives, an unprecedented level of effort is now aimed at the development of hydrogen fuel for automobiles, stationary energy storage, and distributed electricity generation.

This project has expanded the LLNL energy flowcharts to include Energy Information Administration (EIA) projections to 2025 and extrapolations to the timeframe (2050) likely necessary to complete a transition to hydrogen transportation. These projections focus principally on hydrogen production from a variety of sources for use in fuel-cell automobiles. We have also computerized and automated the flowchart generation process to allow very rapid, yet flexible, creation of flowcharts representing a broader spectrum of energy use futures, technology developments, and deployment scenarios.

An Energy Flowchart Adapted for Hydrogen and Transportation

This adaptation process has led to a flowchart substantially richer and somewhat more complex (Figure 2.) than the manually constructed original (Figure 1). Renewable energy resources have been disaggregated to individually show potentially large and intermittent electric generation technologies such as solar, wind, and hydroelectric, while dispachable renewables (biomass, geothermal, etc.) are combined. Electricity generation and distribution have been combined for simplicity, and hydrogen production has been represented explicitly as a central box. End-use energy sectors were reorganized to highlight high value, retail end-uses (transportation, commercial, residential) with industrial and non-fuel uses combined. Special attention is given to transportation, which is “broken down” into three sectors driven by distinctly different market realities: automotive (light-duty vehicles), commercial aircraft, and commercial freight (which for simplicity also includes rail, marine, public transit, and military energy use). These sectors correspond roughly to the categorization(s) used in the Annual Energy Outlook (AEO), produced by EIA using the national energy modeling system (NEMS).

Future Projections and Extrapolation of Energy Demand and Supply

Previous LLNL energy flowcharts relied strictly on historical data and categorizations produced by EIA. The forward looking perspective of this project required projection of many factors influencing the amounts, distribution, and efficiency of energy consumption in the United States over approximately the next 50 years, sufficient to allow a full transition to hydrogen transportation. Rather than attempt projecting the full range of factors 50 years in the future, we have chosen to use simple, transparent, and flexible assumptions that can be modified by the user.

For purposes of this project, we have adopted EIA’s future projections to 2025 as “future historical data” while allowing further linear extrapolation using some or all of historical and projected energy demands from EIA for each end-use sector (residential, commercial, aircraft, etc.). EIA’s projections (or extrapolations from them) of each end-use demand can be individually overridden by the user. In addition, the share of each primary energy source reaching both intermediate (i.e. electricity or hydrogen generation) and end-use energy demands can be user specified or defaulted to EIA projections for 2000-2025. The net effect is that a scenario requiring hundreds of individual assumptions can be implemented with as few as *ten* mouse-clicks. Scenarios (such as scenarios 7-12 shown later in this report) can be concisely summarized and thought of as “Linear extrapolations of EIA projected 2020-2025 end-use demand(s) to 2050, modified by replacing 50 mpg gasoline hybrid vehicles with 80 mpg equivalent fuel cell compressed hydrogen vehicles”.

Automotive Sector Assumptions

The automotive sector is the primary focus of current hydrogen development efforts, and consequently the most richly defined and represented in the LLNL Energy Flow Model. The light-duty vehicle sector allows user inputs of U.S driving age population, annual vehicle miles traveled, and fleet average gasoline vehicle fuel economy. The model indicates reference values for these variables consistent with EIA energy use projections out to 2025. For years beyond 2025, the U.S. driving age population is calculated from U.S. Census Bureau population growth projections (reaching 318 million people of driving age in 2050). EIA projects vehicle miles traveled (VMT) per driver to average 15,000 miles/yr in 2025, up from 12,000 miles/yr in 2005. For years beyond 2025 VMT is linearly extrapolated to reach 19,500 miles/yr in 2050.

The model also allows two other variables to be specified for automobiles: the energy storage penalty for hydrogen fuel (a default value of 10% LHV represents H_2 compression to 10,000 psi) and the relative fuel economy advantage of hydrogen or other alternative fuel vehicles relative to gasoline vehicles (hybrid or conventional). Fuel cell hydrogen vehicles were assumed in this study to achieve 1.6 times greater fuel economy than gasoline hybrid electric vehicles, resulting in projections of 50 mpg gasoline hybrids and 80 mpg equivalent hydrogen fuel cell vehicles.

Useful and Rejected Energy

The model permits user specified values for the efficiency of all energy conversions and end-uses. Guidance available to the user is automatically inferred by calculation from EIA projections from 2000 to 2025 for the electricity generation sector. 80% efficiency is assumed by default for stationary energy end-uses, with transportation energy efficiencies ranging from 40% for commercial freight, 25% for aircraft, and 16%-27% for internal combustion engine automobiles, 40% for hybrid vehicles, and 60% for fuel cell vehicles.

Database Statistics

The model also includes datasheets for statistics and extrapolation linked to the historical and projected database drawn from EIA. These sheets allow for quantitative analysis of trends in individual sectors and statistical quality control of input data easing detection of typographic and other data input errors.

Flowcharts as scenarios

The LLNL energy flowchart model allows for individual model flowcharts to be saved as a scenario. Up to 12 scenarios can be stored in a single file allowing for rapid cross comparison. The scenarios can be exported as graphic files removing detailed text but retaining key assumptions, the projection year, energy use totals for sources, intermediate and end-uses as well overall primary energy use, delivered energy, and rejected energy.

Future Scenarios

For illustrative purposes a preliminary set of 12 scenarios was generated. These scenarios generally represent growing primary energy use with improving efficiency over the next 50 years (scenarios 1-6), along with hydrogen production (scenarios 7-12) to support fueling of a 100% hydrogen fuel cell light-duty fleet projected at 318 million vehicles driven an average 19,500 miles annually in 2050.

Scenario 1: U.S. 2005 EIA Reference Case Projection (97 quads)
(20 mpg average light-duty fleet of 220 million autos)

Scenario 2: U.S. 2025 EIA Reference Case Projection (133 Quads)
(20 mpg average light-duty fleet of 266 million autos)

Scenario 3: U.S. 2050 Reference Case (181 quads)
(20 mpg average light-duty fleet of 318 million autos)

Scenario 4: U.S. 2050 Efficient Electricity Case (167 quads)
(50% efficient electricity generation)

Scenario 5: U.S. 2050 Automotive Efficiency Case (152 quads)
(33 mpg light-duty fleet fuel economy)

Scenario 6: U.S. 2050 Hybrid Vehicle Case (144 quads)
(50 mpg gasoline hybrid light duty fleet)

Scenario 7: U.S. 2050 blended H_2 fuel cell light-duty fleet (146 quads)
("80 mpg" compressed hydrogen light duty fleet)

Scenario 8: U.S. 2050 H_2 light-duty fleet with wind electrolysis (143 quads)
(66% efficient wind electrolysis)

Scenario 9: U.S. 2050 H_2 light-duty fleet with steam methane reforming (143 quads)
(75% efficient natural gas reforming)

Scenario 10: U.S. 2050 H_2 light-duty fleet with biomass gasification (146 quads)
(65% efficient biomass gasification)

Scenario 11: U.S. 2050 H_2 light-duty fleet with coal gasification (149 quads)
(50% efficient coal gasification with CO_2 sequestration)

Scenario 12: U.S. 2050 H_2 light-duty fleet with nuclear H_2 production (153 quads)
(42% efficient thermochemical cycle)

The initial scenarios (1-2) display projected current (2005) and intermediate term (2025) energy use, driven principally by existing demographics, capital stock and infrastructure. Subsequent scenarios (3-12) explore potential changes in energy flows over the longer term (2050) with sufficient lead-time for complete turnover of capital stock (e.g. powerplants, refueling infrastructures, and vehicle fleets). Scenario 3 shows the result of extrapolating EIA projections from 2025 to 2050. Scenario 4 explores the impact of deploying IGCC coal and HTGR nuclear technologies to raise electric generation efficiencies to 50%. This advance is presumed throughout the further scenarios since these technologies are consistent with planned hydrogen generation from nuclear-driven thermochemical cycles, such as the sulfur-iodine (S-I) cycle, or from coal gasification with sequestration. Scenarios 5-6 indicate the additional impact of improving light-duty fleet average fuel economy from 20 mpg to 33 mpg (Scenario 5), and later to 50 mpg (Scenario 6) representing a complete transition to gasoline hybrid vehicles.

Scenario 6 is the baseline 2050 scenario from which scenarios 7-12 are projected, representing complete deployment of "80 mpg" compressed hydrogen fuel cell vehicles. Hydrogen for these vehicles may be produced from a balanced blend of energy resources (Scenario 7), including natural gas, coal, biomass, and (wind) electrolysis with a small (5%) contribution from nuclear thermochemical plants. For comparison, the next 5 scenarios (8-12) produce equal amounts of hydrogen, but solely from wind power, natural gas, biomass, coal, and nuclear energy respectively.

Observations

The 12 scenarios in this report are all based on EIA projections which indicate U.S. population growth will be outpaced by energy use over the next 50 years stemming principally from 1) increasing electrification of energy end-use, and 2) increasing transportation demand, especially for light-duty vehicles. Improving light-duty fleet fuel economy alone (e.g. from 20 mpg to 50 mpg) over this time frame (scenarios 4-6) will likely be insufficient to reduce U.S. petroleum use below today's levels. Full penetration of 80 mpg hydrogen fuel cell vehicles throughout the light-duty fleet by 2050 will reduce petroleum dependence an additional 15.5 Quads (7.3 million barrels/day) over 50 mpg gasoline hybrid vehicles. Producing all of this hydrogen from any individual source will require substantial increased use of that source, and in the case of wind and nuclear energy, a multiplication of otherwise projected supplies. Producing 10.7 quads (100 million tonnes H_2) of hydrogen from a diverse portfolio (scenario 7) will reduce the additional use of individual energy sources to levels comparable to projected growth over the 2005-2050 period.

Expansion of the Energy Flowchart Methodology

Several upgrades to LLNL's existing energy flowchart software can be envisioned. "Difference Map" flowcharts could clearly display the changes between two scenarios. Output could be automated further, allowing for "time-lapse photography" movies at ~1 frame/sec from user specified frames or ultimately energy system transitions interpolated "on the fly" between two user specified scenarios using s-curve or linear paths. Developing flowcharts freely "switchable" between multiple unit systems (Quads, EJ, TW, GW, kWh, GtC, mmb/d of oil equivalent, million metric tonnes of H_2, trillion cubic feet (TCF) of natural gas, and Billions ($B) of dollars of energy value) would aid comprehension greatly for audiences from varying fields. Implementing flowcharts that permit direct user specification of *either* input or output shares of, for example, hydrogen and electricity generation, would speed the development of scenarios on the fly, likely to the point of real-time response to audience questions.

In addition to software improvements the flowcharts should ultimately be expanded to study greenhouse gas emissions in addition to energy use and potentially further disaggregate end-uses (lighting, electronics, heating, cooling, hot water, etc.) and transportation (business & vacation air travel, daily commuting, errands, shopping etc.). Flowcharts could also be implemented to communicate the potentially dramatic differences at different <u>spatial</u> and <u>temporal</u> scales (i.e. states, cities, businesses, schools, households over annual, seasonal, weekend, weekday, and diurnal cycles).

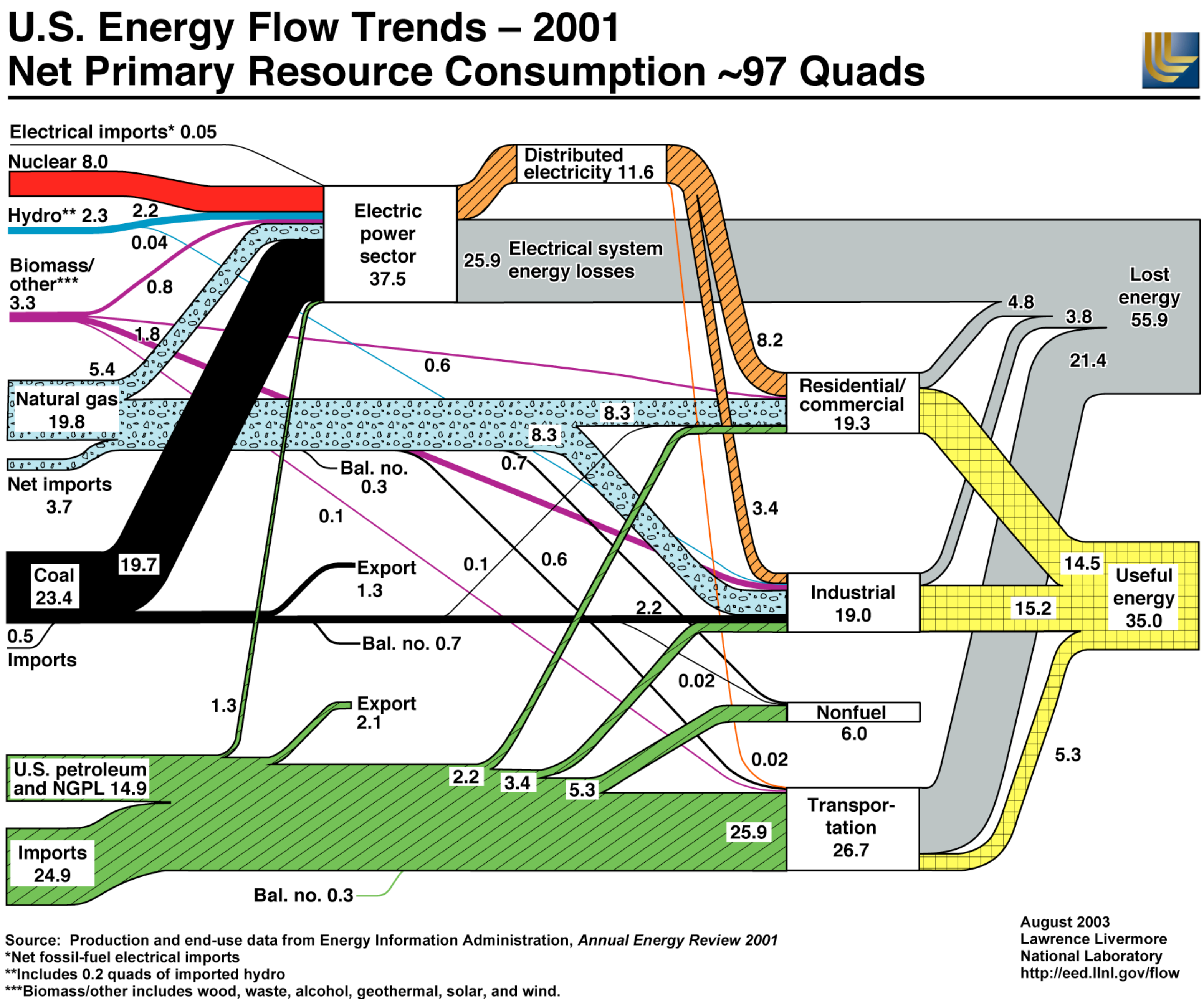


Figure 1. U.S. Energy Flow for 2001 was 97 Quads (Quadrillion Btu) according to the Energy Information Administration's *Annual Energy Review 2001*. Transportation and electricity generation account for 70% of energy use and up to 85% of lost energy.

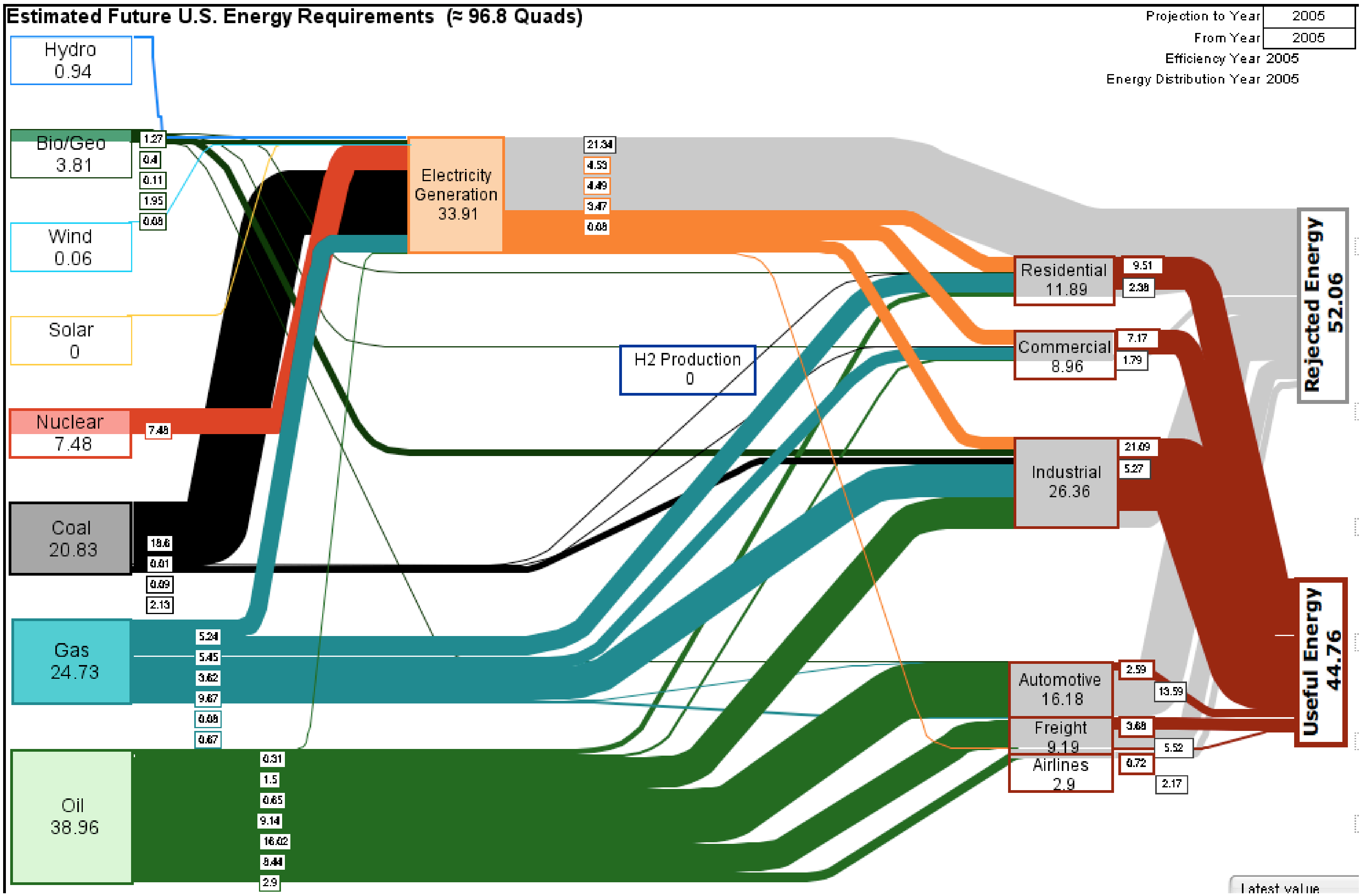
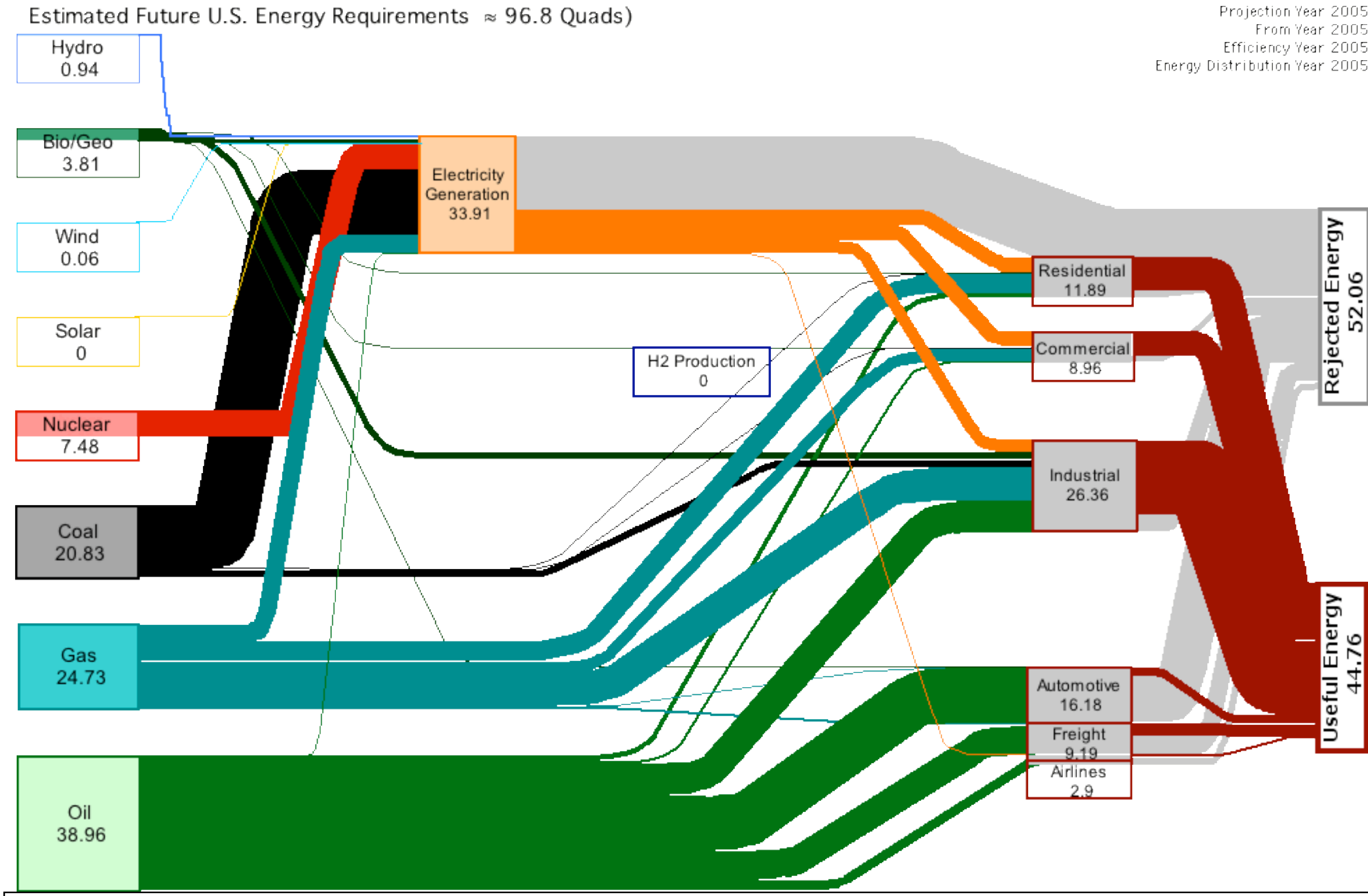
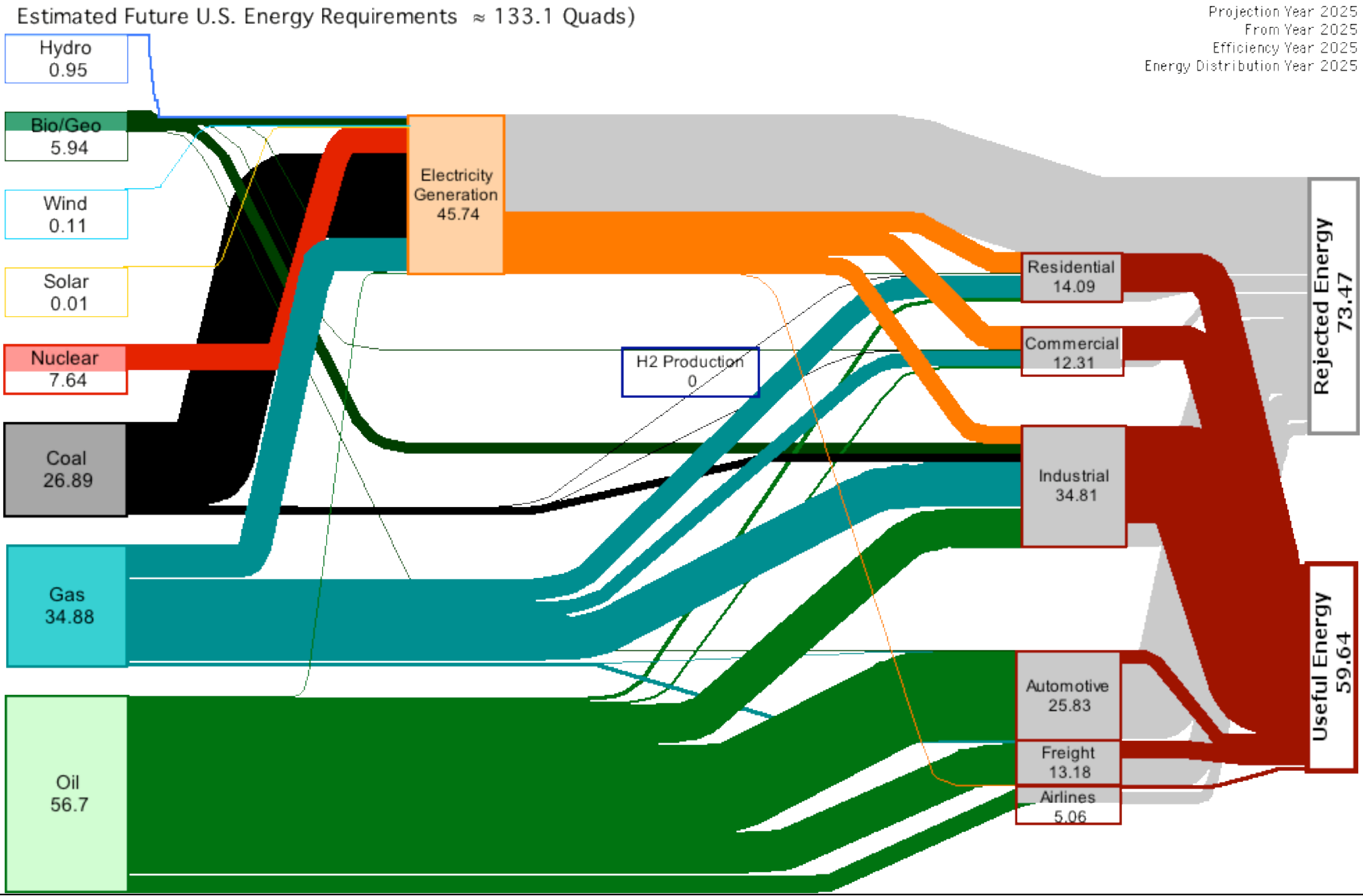


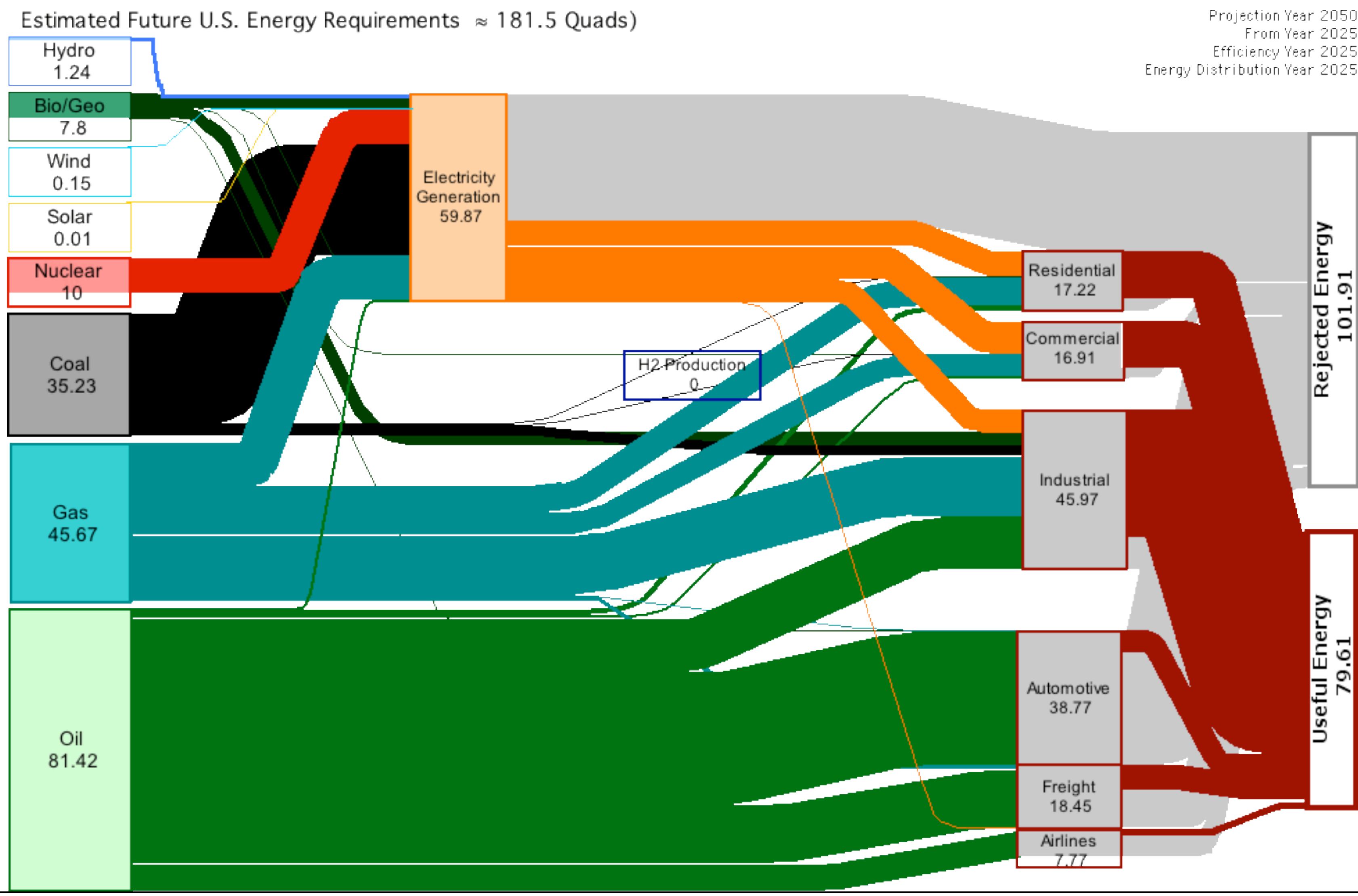
Figure 2. Typical output from LLNL's automated U.S. Energy Flow model.
This figure displays projected 2005 U.S. energy flows adapted from EIA's 2003 *Annual Energy Outlook*.



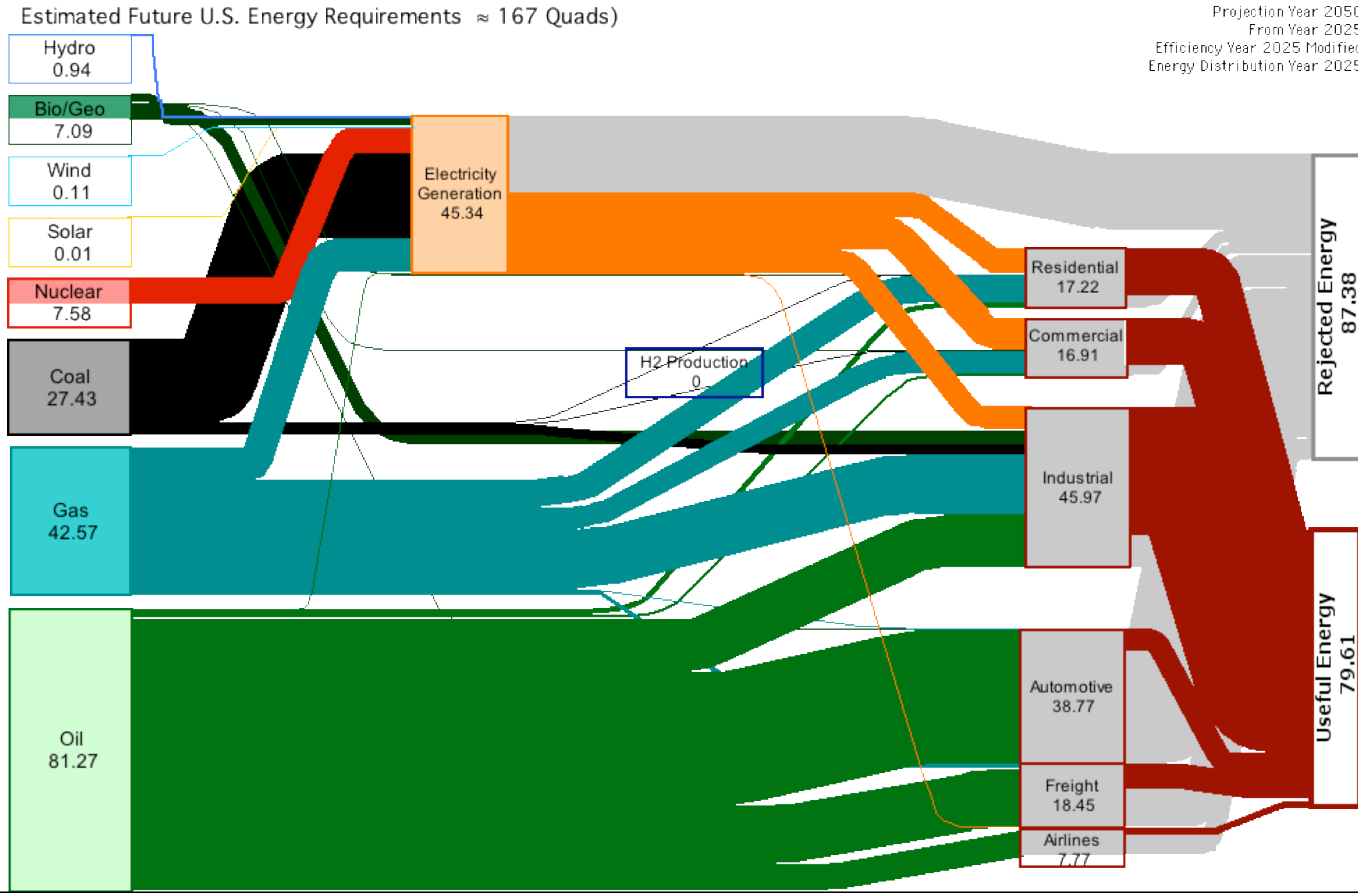
Scenario 1. U.S. Energy flow is projected to be 97 Quadrillion Btu in 2005 by EIA's *Annual Energy Outlook.* Light-duty vehicles will consume 16.2 Quads (~7.6 mmb/d) averaging 20 mpg over 11,800 miles/yr per capita of driving age population (220 million)



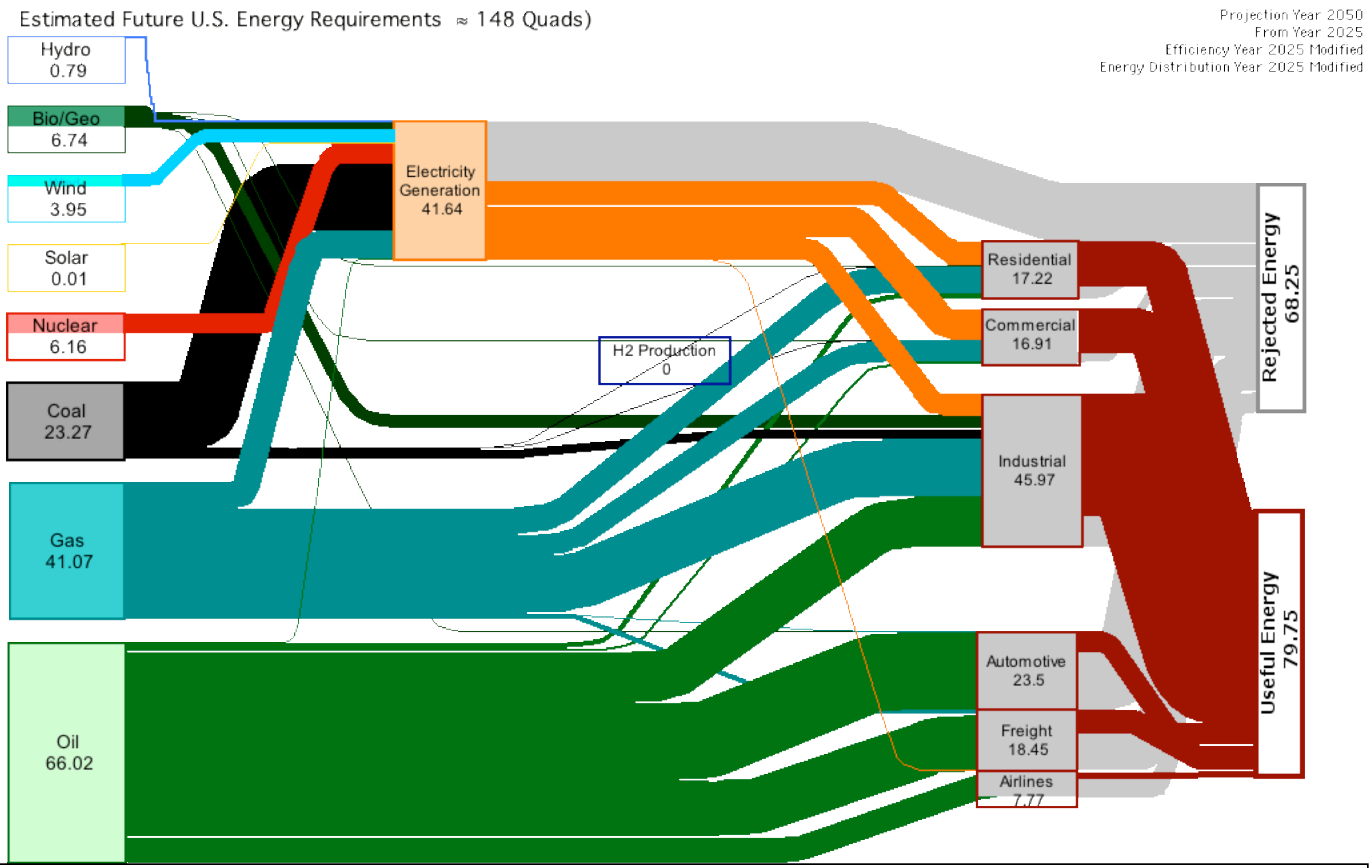
Scenario 2. ***Annual Energy Outlook 2003*** **projects U.S. energy flow to reach 133 Quads in 2025, driven by electrification of residential & commercial sectors and dramatic increases (16 Quads) in petroleum use for freight and passenger transport**



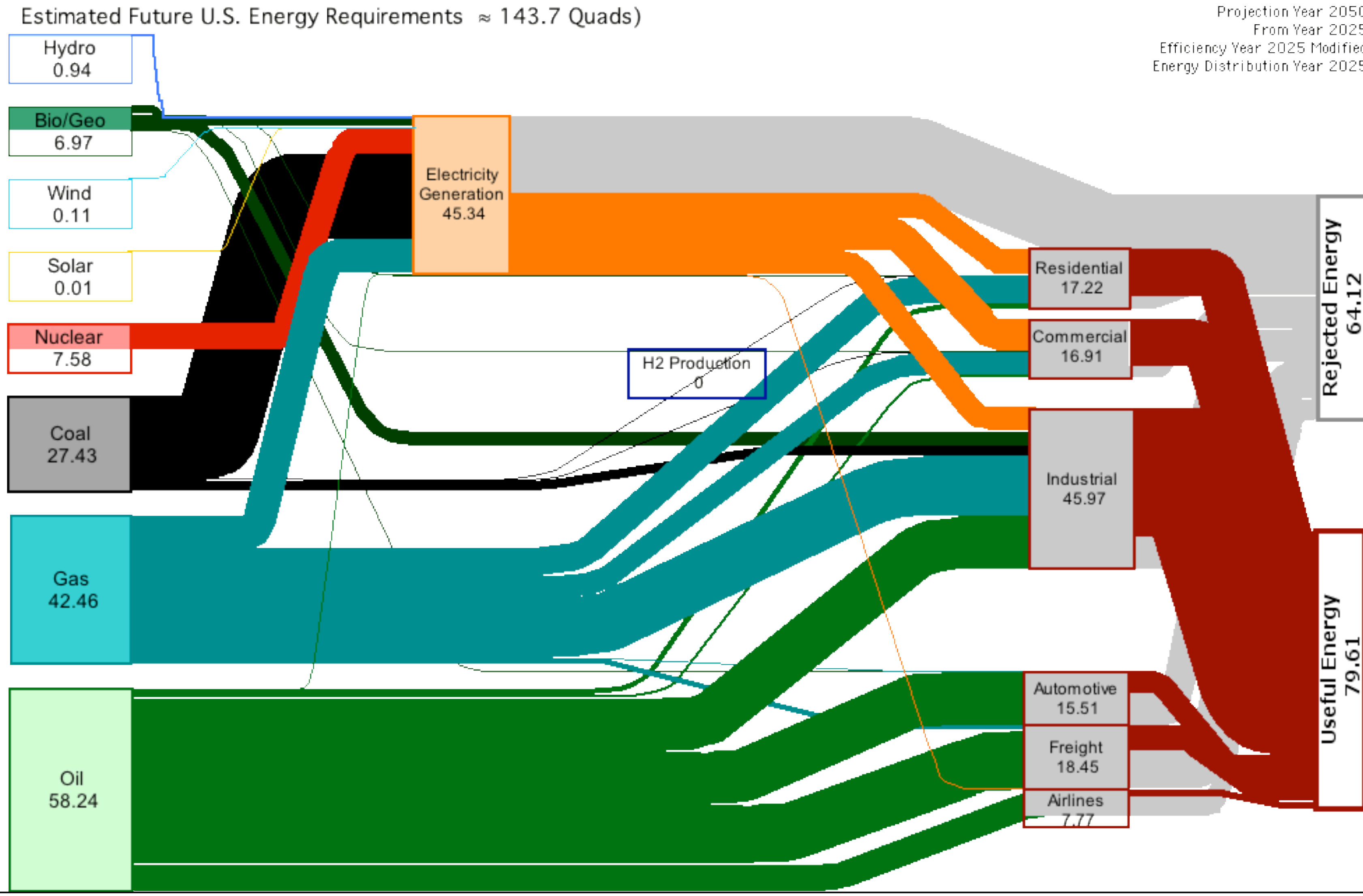
Scenario 3. Linear extrapolation of *Annual Energy Outlook* projections for 2020-2025 out to 2050. A driving age population of 318 million, averaging 19,500 miles driven per year in 20 mpg vehicles, requires 39 Quads of petroleum or 18 million bbl/day.



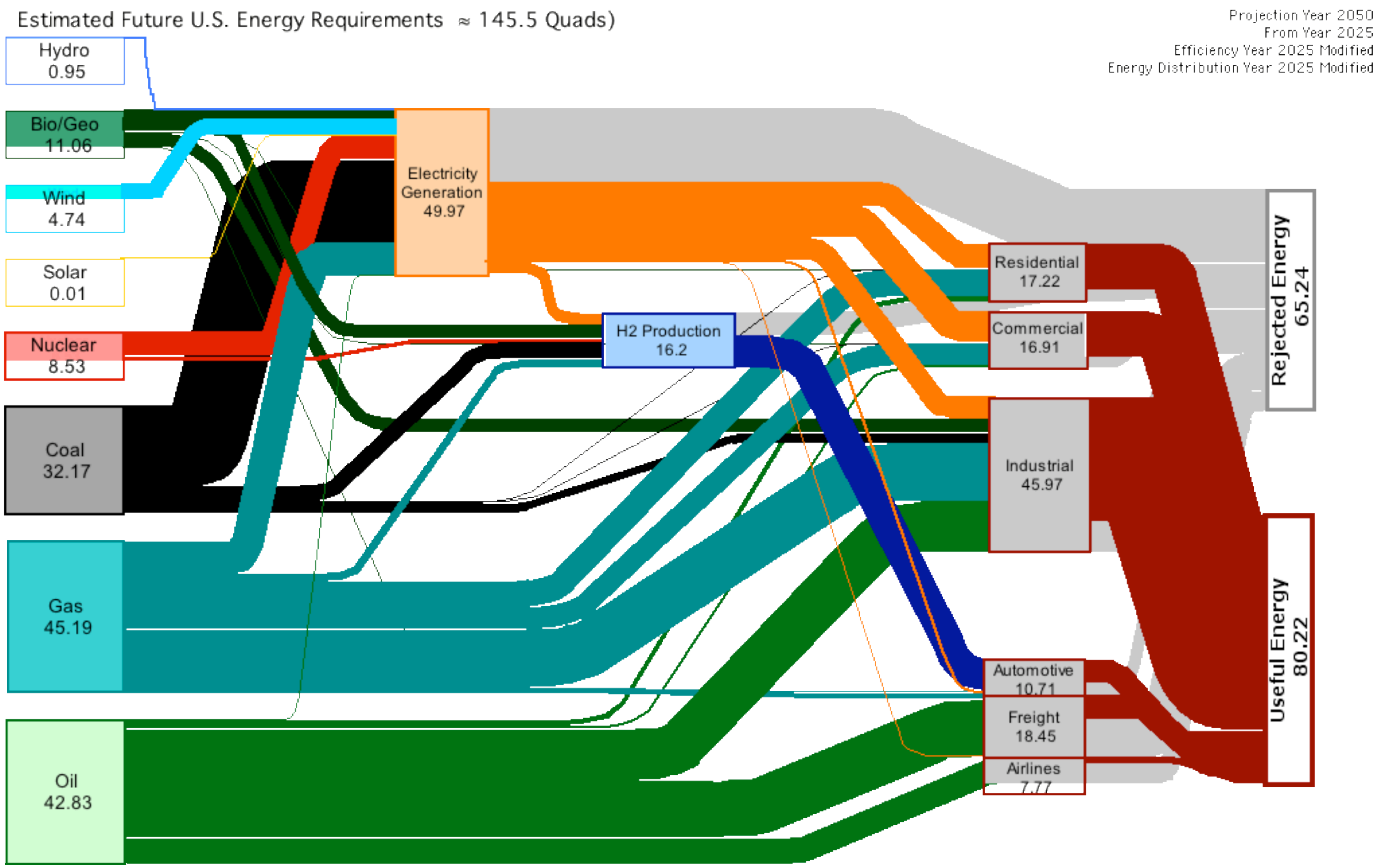
Scenario 4. Linear extrapolation of *Annual Energy Outlook* projections for 2020-2025 out to 2050, with the additional assumption that electric generation efficiency of coal, biomass, and nuclear plants is increased to 50%.



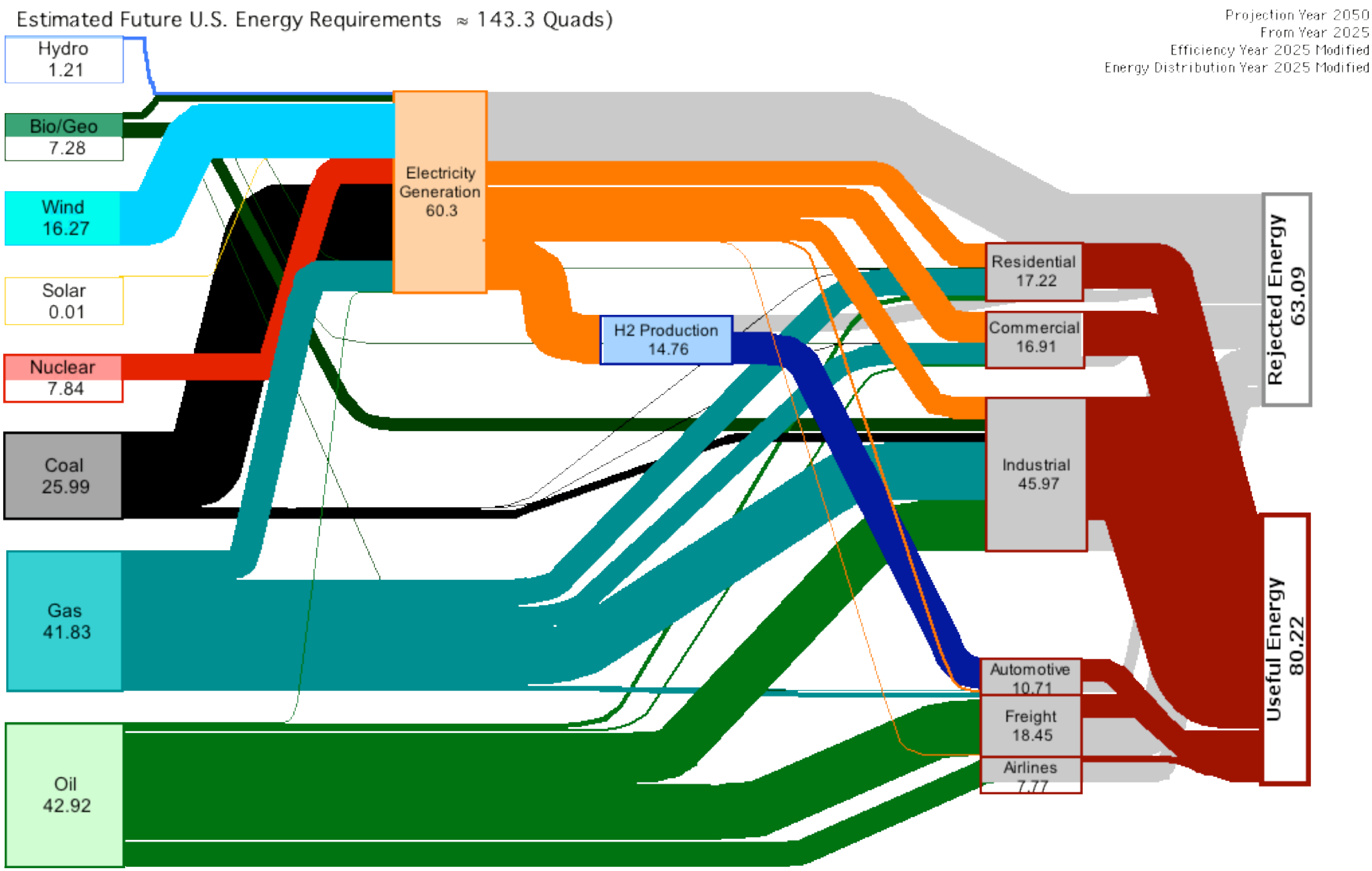
Scenario 5. Linear extrapolation of *Annual Energy Outlook* projections for 2020-2025 out to 2050. Coal, biomass, and nuclear electric plants are assumed 50% efficient, with a 33 mpg average light-duty fleet in addition.



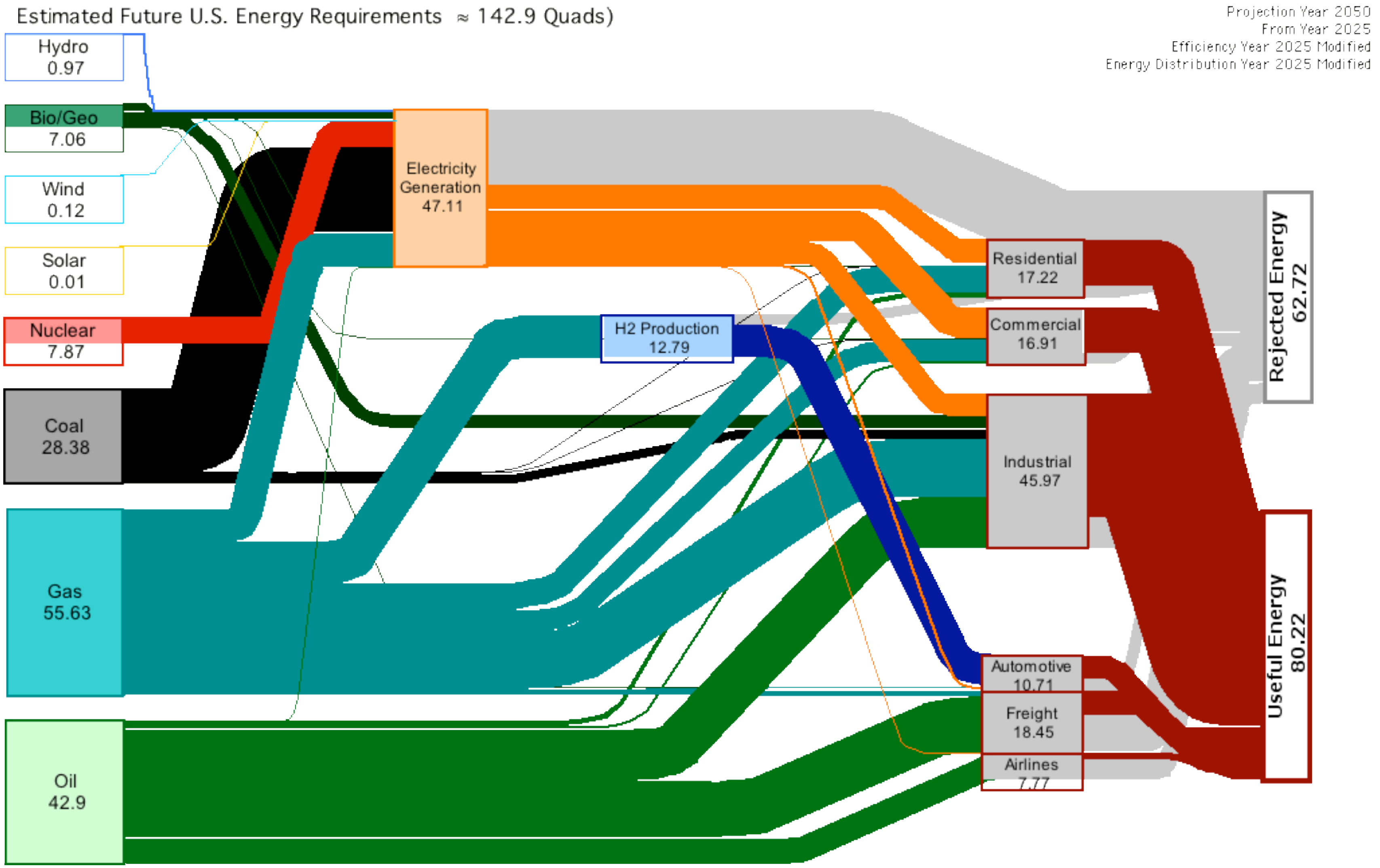
Scenario 6. Linear extrapolation of *Annual Energy Outlook* projections for 2020-2025 out to 2050. Coal, biomass, and nuclear plants assumed to achieve 50% efficiency. The light-duty fleet assumed to average 50 mpg using gasoline hybrids.



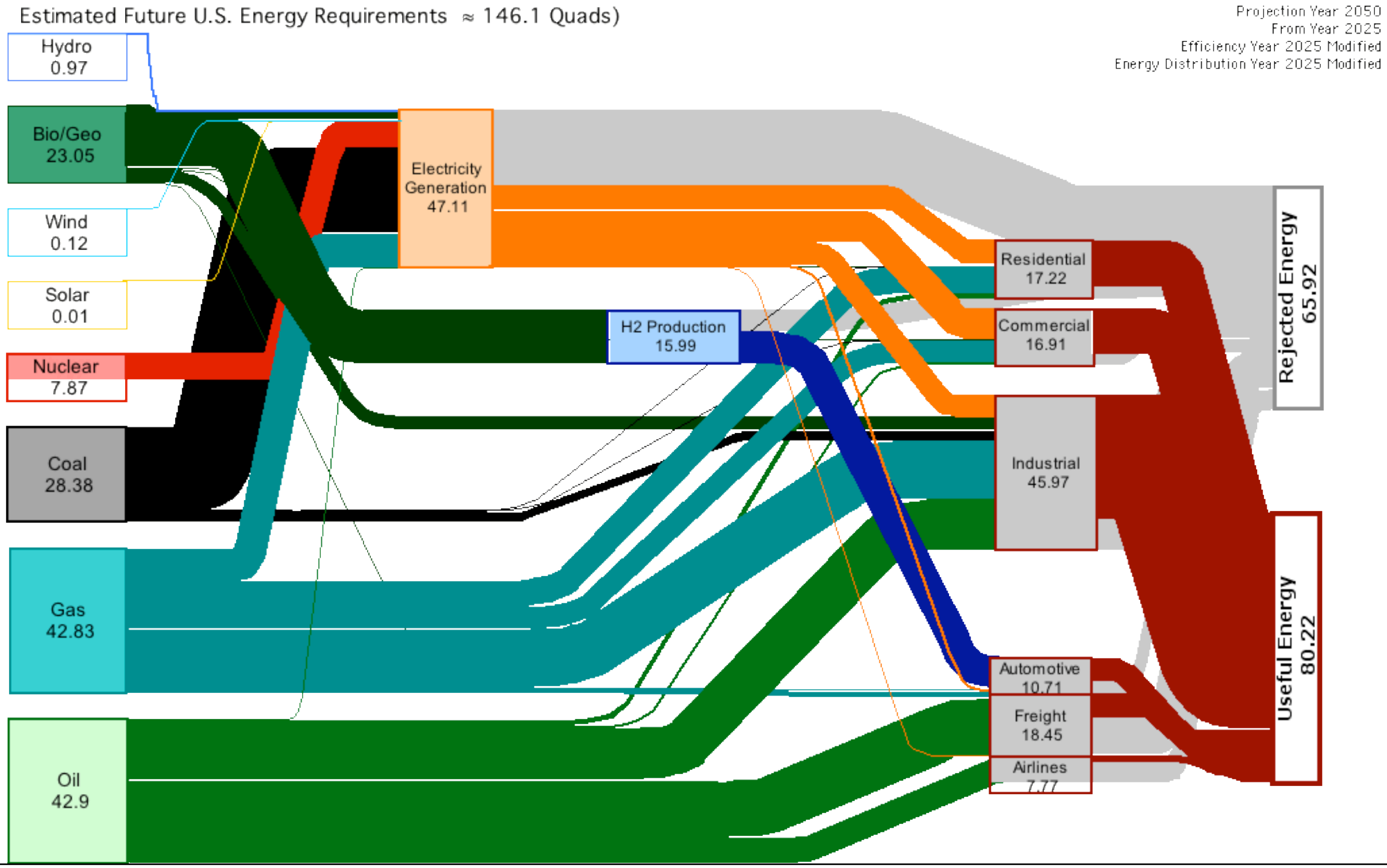
Scenario 7. Scenario 6 except the light-duty fleet transitions entirely to 80 mpg equivalent hydrogen (H_2) fuel cell vehicles by 2050. H_2 produced using a mix of gas (20%), coal (25%), biomass (25%), wind electrolysis (25%), and nuclear thermochemical (5%).



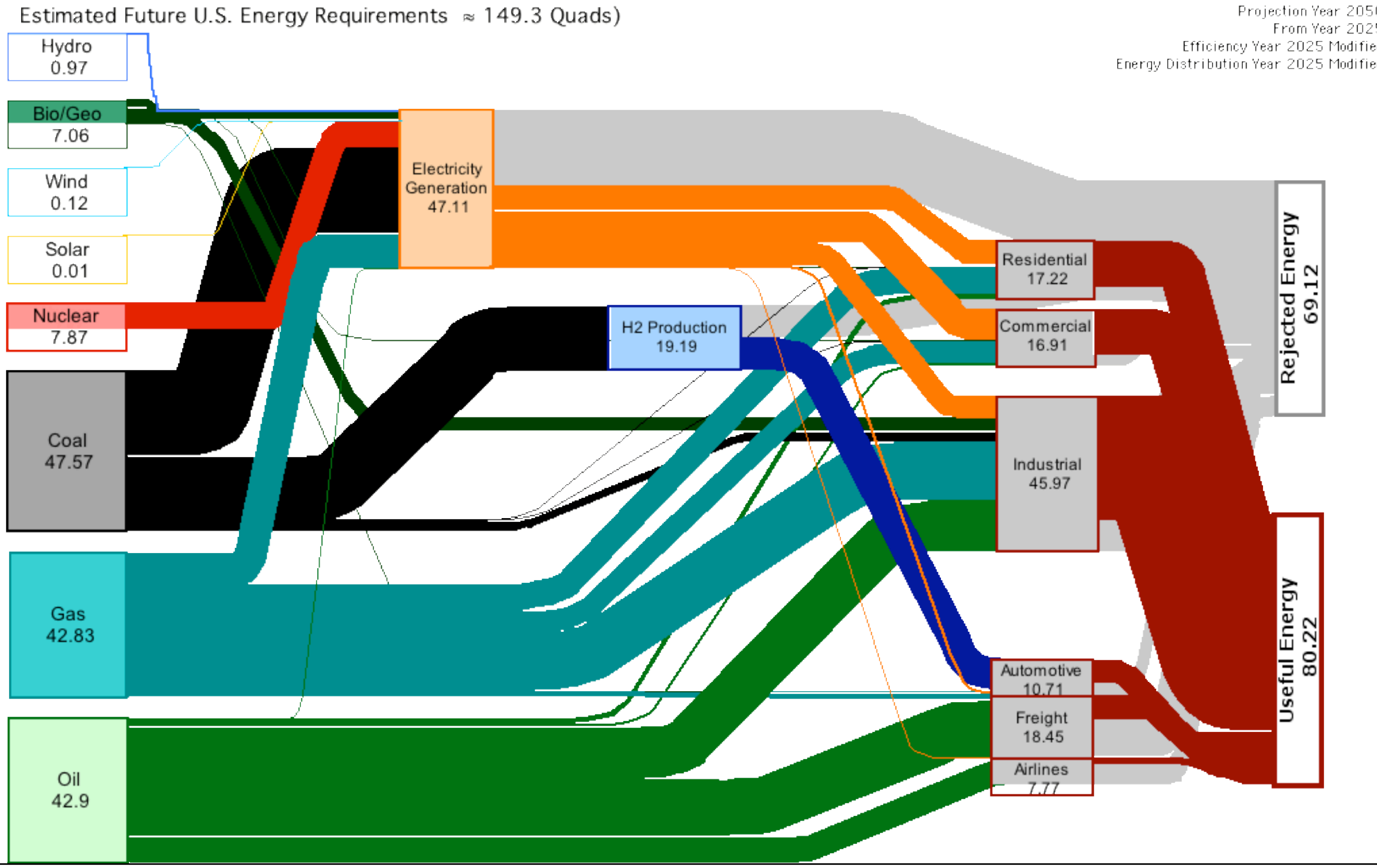
Scenario 8. The U.S. light-duty fleet transitions to "80 mpg" 10,000 psi compressed hydrogen (H_2) fuel cell vehicles by 2050. 15 Quads (~ 4.3 trillion kWh) of wind electricity produces H_2 by water electrolysis with 66% efficiency (LHV basis).



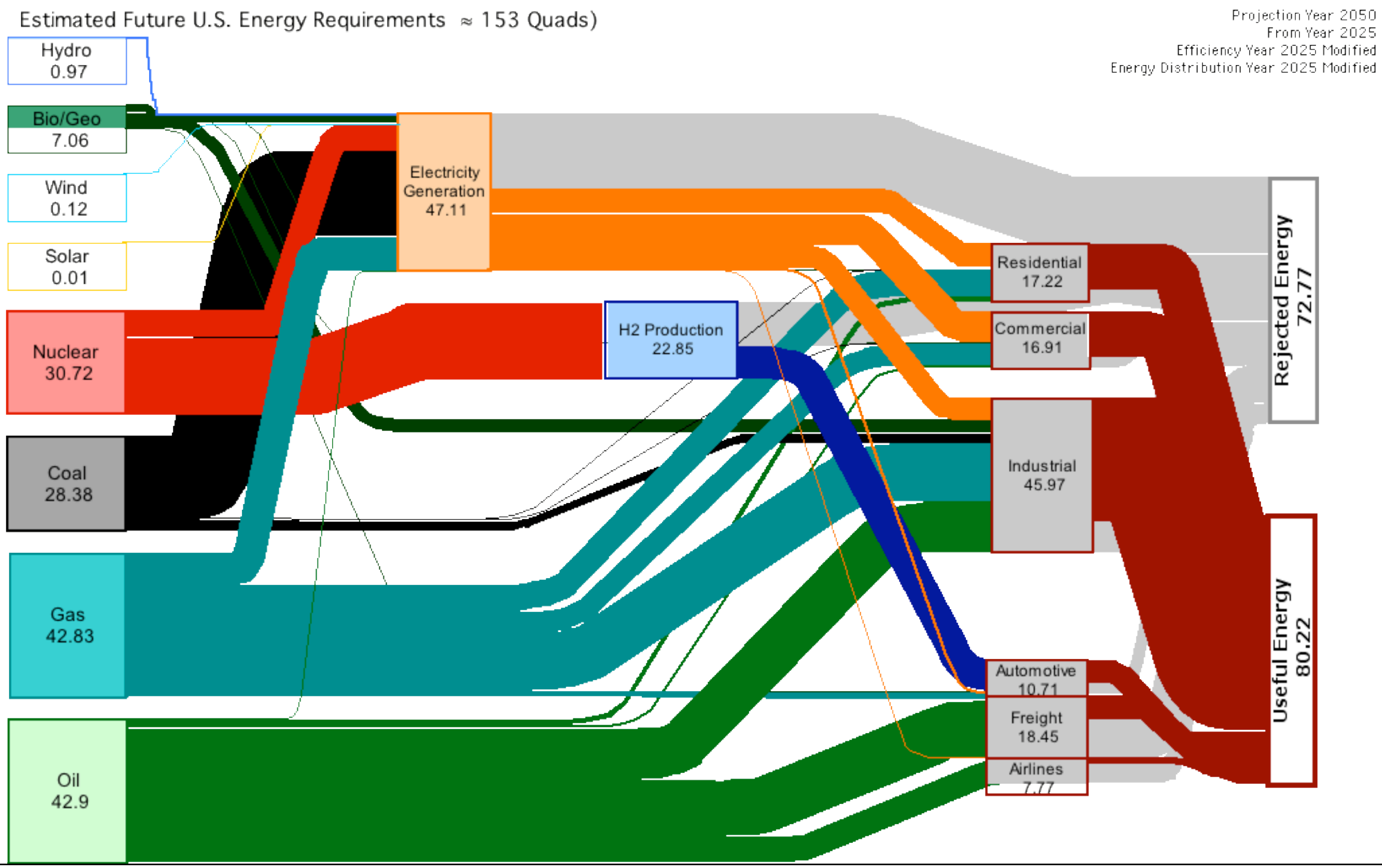
Scenario 9. The U.S. light-duty fleet transitions to "80 mpg" 10,000 psi compressed hydrogen (H_2) fuel cell vehicles by 2050. 10.7 Quads of H_2 are produced using 75% efficient (LHV basis) steam reforming of natural gas, saving 7.3 barrels of oil daily.



Scenario 10. The U.S. light-duty fleet transitions to "80 mpg" 10,000 psi compressed hydrogen (H_2) fuel cell vehicles by 2050. 16 Quads of cellulosic biomass produce 100 million tonnes of H_2/yr with 60% efficiency (LHV basis).



Scenario 11. The U.S. light-duty fleet transitions to "80 mpg" 10,000 psi compressed hydrogen (H_2) fuel cell vehicles by 2050. 19 Quads of coal are gasified and sequestered to produce 100 million tonnes of H_2/yr with 50% efficiency (LHV basis).



Scenario 12. The U.S. light-duty fleet transitions to "80 mpg" 10,000 psi compressed hydrogen (H_2) fuel cell vehicles by 2050. 23 Quads of nuclear fuel produce 100 million tonnes of H_2/yr with 42% efficiency (LHV basis) using the Sulfur-Iodine cycle.